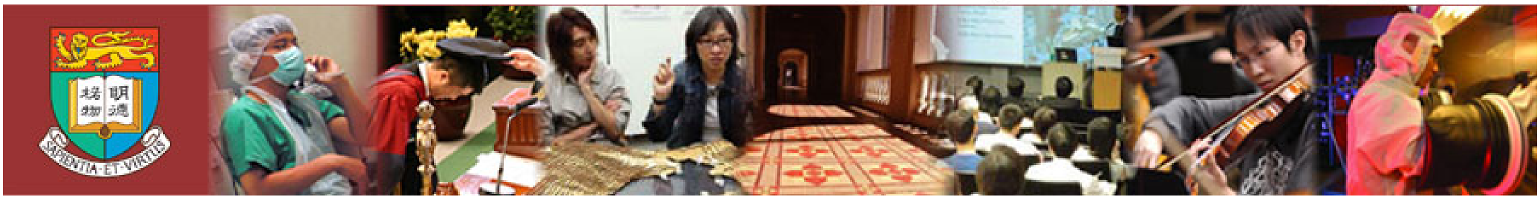

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Field-Effect Ferroelectric-Semiconductor Solar Cells

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***Abstract* — Traditional photovoltaic devices employ limited semiconductor materials largely due to the P-N junction structure. We have developed a new kind of field-effect ferroelectric semiconductor solar cells. Prototype cells have been demonstrated successfully. Substantial photovoltaic effect and rectifying behavior were experimentally observed. In addition, simulation study was conducted to indicate that the induced electric field due to the bound surface changes of the ferroelectric could be extended into the semiconductor. The simulation results are consistent with experimental observations. This unique device structure offers a promising alternative to achieve novel solar cells. The new cells are not P-N junction based, and in principle offer more flexibility in materials selection and optimizing charge generation, separation and collection for achieving high performance solar cells.**

***Index Terms* — photovoltaics, ferroelectric, semiconductor, field-effect, polarization.**

I. INTRODUCTION

Charge carrier separation is one key step in photovoltaic devices. The traditional P-N junction makes use of the spatial variation in electronic environment and is a classic model for realizing this function. However, this kind of structure limits choices for materials to form a working junction due to issues such as lattice mismatch, doping, and band alignment. Furthermore, either homo-junction or hetero-junction inevitably introduces defect states that act as centers for carrier recombination or trapping [1]. In contrast, ferroelectric photovoltaic (FPV) cells provide a fascinating charge separation mechanism that avoid these issues, and thus have attracted much attention [2-4]. A typical FPV cell, consisting of a ferroelectric layer sandwiched between two electrode plates, may have an internal electrical field throughout the bulk region originating from electrical polarizations that are not completely compensated by screening charges [5]. Consequently, FPV even can obtain open circuit voltage above band gap [6, 7]. However, ferroelectric materials are typically highly insulating because of large band gaps [8], which limits the absorption especially of visible light. Thus, ferroelectrics are not ideal absorption materials in photovoltaics.

In this work, we demonstrate a new concept of solar cells, i.e., field-effect ferroelectric-semiconductor solar cells (FEFSSCs), which combine ferroelectric and semiconductor materials. The new cells avoid the P-N junction structure and use the bound surface charges of the ferroelectric to separate photon-generated charge carriers in the semiconductor absorber. This unique architecture can be adapted to any semiconductor materials in principle, and thus provides significantly more freedom in material selection. In this study, we applied $BaTiO_3$ (BTO) and silicon to make FEFSSCs, and successfully realized charge carriers separation and collection in silicon through the asymmetric ferroelectric polarization.

II. EXPERIMENTAL

Fig. 1 schematically depicts the working principles of FEFSSCs. An FEFSSC mainly consists of a ferroelectric layer, a semiconductor layer, a pair of poling electrodes, and a pair of counter electrodes. The poling electrode patterns align well with those of anode and cathode, respectively. With these electrodes, we can apply external voltage to polarize the ferroelectric film in a fashion as that shown in the figure. These asymmetric bound surface charges are expected to induce an electric field in the semiconductor so that photon-generated charge carriers can be separated therein. To prepare real solar cells, we selected p-type single crystalline silicon and poly-crystalline $BaTiO_3$ as the semiconductor absorber and ferroelectric layer, respectively. We choose these materials to demonstrate the new concept due to mature technologies. During poling process, we kept the poling electrodes (made of silver) grounded, and applied +18V on Au cathode and -18V on Ti anode simultaneously, which is defined as forward polarization.

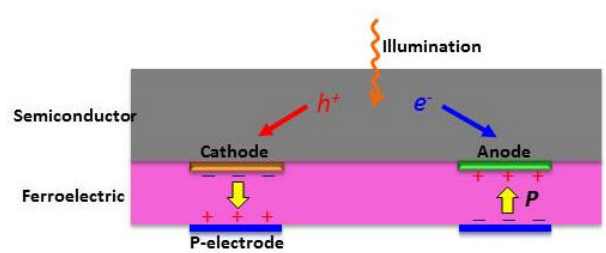

Fig. 1. Schematic of a FEFSSC and its working principles.

III. RESULTS AND DISCCUSION

Fig. 2 shows I-V curves of a typical FEFSSC at different polarization states and conditions. As shown in Fig. 2(a), under dark condition, the virgin curve is linear and shows high resistivity. However, after forward polarization, a substantial diode-like curve shows up. The rectification ratio, defined as the ratio of positive current over negative one at V = ±0.5V, respectively, is 133. This rectifying behavior is more vivid in the log scale plat (see the inset of Fig. 2(a)). It is obvious that the polarization directly changes the conductive behavior of the device. This diode-like behavior of dc conduction is constantly observed in all cells, which implies that our cells may show the same photovoltaic effect as in traditional P-N junction solar cells.

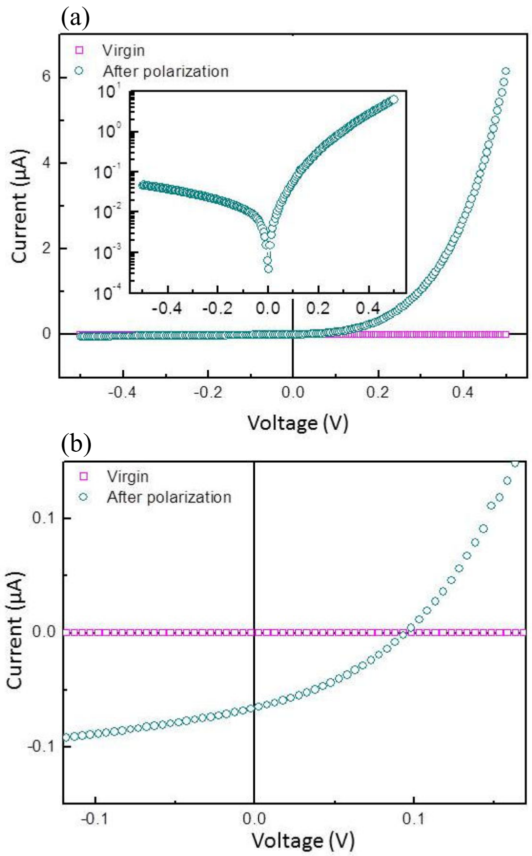

Fig. 2. I-V curves of a typical FEFSSC under the virgin (pink line) and after-forward-polarization (green curve) states, respectively. (a) Under dark condition. Inset is the plot in log scale for the forward-polarization state. (b) Under illumination condition.

The I-V curves under illumination are shown in Fig. 2(b). It is obvious that there is no photovoltaic output for the virgin state. After forward polarization, however, the I-V curve shifts downward under illumination, exhibiting the photovoltaic effect with V_{oc} of 93.0 mV and I_{sc} of 0.067 μA. Because the band gap of BTO is 3.2 eV and the light is shot form the thick silicon side, the photon-generated charge carriers are mainly limited to be in the silicon layer for electricity generation.

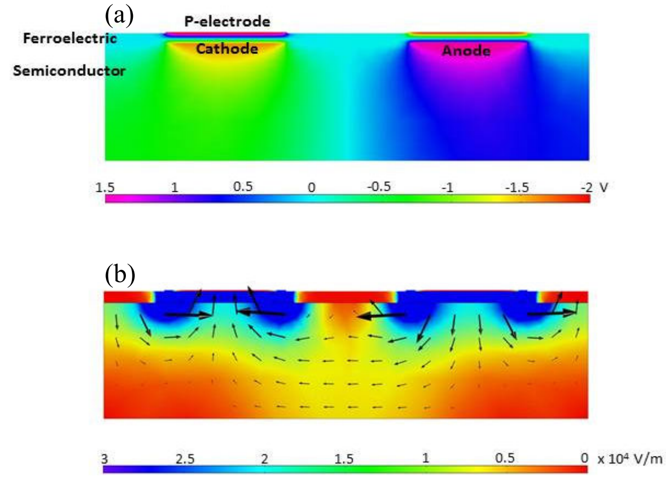

Fig. 3. Simulation of a possible optimized cell. (a) Potential distribution. (b) Electric field distribution.

To explain how the bound surface charges induce electric field in the semiconductor, we have turned to the theoretical simulation with finite-element method using COMSOL®. Fig. 3 (a) shows the potential distribution of a possible optimized cell with Al as electrodes. The thickness of silicon is 100 μm, and the thickness of Al is 1 μm. The distance between Al electrodes is 100 μm, the electrodes width is 100 μm, and relative permittivity of silicon and Al are 11.9 and 7.8, respectively. In the simulation, the anode area was set to have a charge density of 0.01 C/m^2, and the cathode area of -0.01 C/m^2. The electric field distribution is depicted in Fig. 3 (b). As black arrows indicate, overall the electric fields point from anode to cathode. When the Si absorbs sunlight, photon-generated electrons and holes will move to the anode and cathode, respectively, under the influence of the induced electric field. The simulated results are consistent with experimental observations at least in terms of current flow direction. It should be pointed out that although in the simulation, we only focused on BTO and silicon materials, any combination of ferroelectric and semiconductor materials can be utilized in principle.

Our results, indeed, suggest that the bound surface charges can induce electric field extended into the silicon layer. Furthermore, the field strength in FEFSSCs can be tuned to make it comparable to that of a typical P-N junction. Note though that the photocurrent in FEFSSCs is drift current dominated, which is different from that of traditional P-N junction based solar cells.

A potential issue is the screening effect due to the metal electrodes, which weakens the induced electric field in the semiconductor [9]. Also, the I-V curves in Fig. 2 indicate high resistivity and low current. It is reasonable then our cells show low performance. These issues may be solved through careful design of electrodes and device layout [10]. In this study, we only focus on the concept demonstration of this new device.

IV. CONCLUSIONS

In summary, we successfully demonstrated a new type of solar cells called FEFSSCs. We applied $BaTiO_3$ and silicon to make FEFSSCs that show the rectifying behavior and photovoltaic effect. In addition, theoretical simulation showed that the induced electric field due to the bound surface changes of the ferroelectric could extend into the semiconductor for realizing charge separation, which is consistent with experimental results. This unique device structure is promising in achieving affordable and high performance solar cells.

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